

**EUROPEAN PATENT APPLICATION**

Application number: 87850100.6

Int. Cl.: **H 02 P 6/02, H 02 P 8/00**

Date of filing: 25.03.87

Priority: 18.04.86 SE 8601802

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Date of publication of application: 21.10.87  
Bulletin 87/43

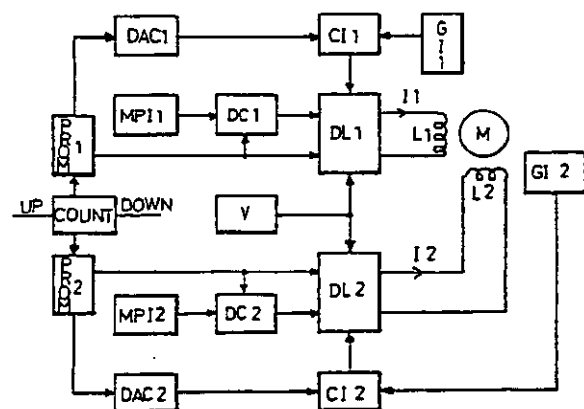
Designated Contracting States: **DE FR GB IT NL**

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**Method and apparatus for controlling a motor.**

The invention relates to a method and apparatus for controlling the current ( $I_1$ ,  $I_2$ ) through a stator winding ( $L_1$ ,  $L_2$ ) of a motor ( $M$ ) which is supplied with energy from a voltage source ( $V$ ) via a drive circuit ( $DL_1$ ,  $DL_2$ ). The drive circuit is controllable such as to provide at least three different operational states, of which a first normally signifies increasing or maintained magnitude of the current, a second normally signifies shutting down or decreasing the current comparatively slowly and a third operational state normally signifies shutting down or reducing the current comparatively rapidly or at least quicker than in the second operational state. In a method and apparatus in accordance with the invention the desired value time sequence is sensed, and at least the possibility of control so that entry into the third operational state is limited in time in response to the result of sensing the desired value time sequence.

The method and apparatus are primarily intended for micro-stepping of a two-phase stepping motor with permanently magnetized rotor.



incremental motion control systems and devices, University of Illinois; "TECHNOLOGY of MICROSTEPPING, OEM DESIGN," October 1983, pp 69-71; and to "Microstepping: Small Steps Turn Into Big Improvements" by E. Slingland, POWER CONVERSION INTERNATIONAL, October 1983, pp 20-25.

- 5 Many drive circuits are known for supplying current to stepping motors from voltage sources and regulating the phase currents through the stator windings. It is also well-known in these cases that current decline can be different for different drive circuits and that different operating conditions can give differently rapid current decline in a single drive circuit. Of special interest in  
10 connection with the present invention are drive circuits including controllable switches, which are intermittently controlled to be in a conductive or blocking state, whereby the current through a stator winding can be regulated towards a desired value. The basic principles for such drive circuits and such regulation are well-known to one skilled in the art and are therefore not described here.
- 15 The first and last of the above-mentioned references are recommended to one unskilled in the art, and apparatus and a method illustrated on page 23 in the POWER CONVERSION INTERNATIONAL reference, may be of special interest for comparison with a preferred embodiment of the present invention.

#### DISCLOSURE OF INVENTION

- Problems can occur in the operation of stepping motors, particularly when there  
20 are large demands on velocity, acceleration and retardation, in spite of a modern motor structure and modern drive circuits. These problems may take the form of vibrations and noise, as well as deviations between desired and actual rotational angle. Certain problems may be traced to resonance phenomena and mechanical properties of the motor structure, while others at  
25 least partially depend on the drive circuit and electrical properties of the motor structure, such as stator winding inductance. In certain operational cases, the drive circuits in known methods and apparatus have therefore not managed to regulate the stator current towards its desired value with sufficient accuracy. In certain cases the current has not been reduced sufficiently quickly in time  
30 with the desired value, and in other cases the current has oscillated heavily about the desired value so that too large a current ripple has been obtained. The object of the invention is to solve, or at least reduce such problems in

value successively decreases.

The operational states, which may be four in bipolar drive circuits, are achieved in accordance with the invention by controlling switches in the drive circuit such as to put them into different combinations of conductive and/or blocking  
5 states. At least partially, the drive circuit can be of a conventional type and the three or four combinations of conductive or blocking states of these switches can be of a kind already known per se.

The distinguishing features for a method and an apparatus in accordance with the invention are more correctly expressed in the disclosures of the claims, the  
10 subordinate claims also disclosing preferred embodiments.

#### BRIEF DESCRIPTION OF DRAWINGS

Figure 1 is a greatly simplified block diagram of an embodiment of an apparatus in accordance with the invention, for use in explaining certain fundamentals of a method in accordance with the invention.

Figure 2 is a simplified block diagram of an embodiment of the invention for a  
15 two-phase motor.

Figures 3a and 3b illustrate a more detailed diagram of how a motor can be controlled with the aid of an apparatus in accordance with the invention.

Figure 4 illustrates a first integrated circuit which can be made a part of an apparatus for microstepping a two-phase stepping motor according to Figures  
20 3a and 3b.

Figure 5 illustrates a second integrated circuit which can be a part of an apparatus for microstepping a two-phase stepping motor according to Figures 3a and 3b.

Figure 6 illustrates an embodiment of a circuit which may preferably be  
25 included in an apparatus in accordance with the invention for implementing a preferred embodiment of a method in accordance with the invention.

Figure 7 illustrates a time sequence for voltages and currents in connection with an embodiment according to Figure 6.

Figure 8 illustrates stepwise changing desired current values and corresponding  
30 actual current values obtained when the drive circuit was prevented from using the second and third operational states during certain times of the time

So far, the described function of the method and apparatus according to Figure 1 is well-known in principle. However, in accordance with the invention, the possibility of switching at least to the third combination is limited in time in response to the desired value time sequence. The control means thus has a  
5 second input for information PI concerning this limitation, which can be rather different in different embodiments of the method and apparatus in accordance with the invention. The control means further includes control limiting means arranged to limit, in response to the received information PI, the ability of the control means, at least with regard to putting the switches into the third  
10 combination. In certain embodiments the ability of the control means to put the switches into the second combination is preferably limited in time in response to the desired value time sequence. In such embodiments the information PI may signify mutually dependent or independent limitations of the possibilities of putting the drive circuit into different operational states. The object of  
15 limiting the control of the control means in time, i.e. all three said operational states not always being available for regulating the stator winding current towards its desired value, is to achieve better current regulation. By this limitation in time, the current through the stator winding in a method and apparatus in accordance with the invention may be rapidly caused to follow  
20 changes in the desired value without too great a current ripple. The control of the drive circuit is preferably limited so that entry into the third operational state cannot occur during certain parts of the desired value time sequence, when the absolute magnitude of the desired value substantially increases, possibly also during certain parts when the absolute value of the desired value is  
25 substantially constant. Control of the drive circuit is also preferably limited so that entry into the second operational state cannot occur during certain time intervals, when the absolute value of the desired value decreases substantially. Control of the drive circuit is also preferably limited during certain parts when the absolute magnitude of the desired value sinks substantially, so that entry  
30 into the third operational state can only take place during special time intervals of these parts. The limitation in time of the possibilities of controlling the drive circuit is preferably such that during the whole, or greater part of the desired value time sequence the drive circuit can be controlled to enter into either the second or the third operational state, but not any of the second and the third  
35 states. On the other hand, the possibility of controlling entry into the first operational state is not normally limited in time, except possibly in bipolar

then be adapted to prevent putting DL1 and DL2 into the third operational state during a part of the time sequence of  $I_{1R}$  and  $I_{2R}$  when the magnitude of the desired value increases with time, possibly at least until this magnitude is at least just as great as the one given respectively by MPI1 and MPI2.

5 Alternatively, or in addition, DC1 and DC2 may be adapted to at least periodically prevent entry into the second operational state during parts of the time sequences of  $I_{1R}$  and  $I_{2R}$ , when the desired value decreases after having attained the value given by MPI1 and MPI2. Optionally, two or more values can be stored in MPI1 and MPI2, thus enabling certain limitation of the possibility

10 of entry into an operational state to be dependent on whether the desired value from PROM1 and PROM2, valid for the instant, or the absolute magnitude of the desired value is under two or more values stored in MPI1 and MPI2, or lies between two values stored in MPI1 and MPI2, or is over two or more values stored in MPI1 and MPI2. For example, the possibility of entry into the third

15 operational state can be limited to times when magnitude of the desired value is decreasing and is between two values stored in MPI1 and MPI2.

For controlling the switches included in the respective drive circuit DL1 or DL2 such as to enter into one of the three combinations of conductive and blocking states, or possibly four such states in bipolar drive circuits, the respective drive

CI 2 20 circuit is connected to C11, DC1 and PROM1 as well as C11, DC2 and PROM2, information concerning desired current direction in the respective stator winding for bipolar drive circuits being obtained from PROM1 and PROM2 in the form of a polarity signal SIGN1 and SIGN2.

To facilitate understanding of the invention, the block diagram in Figures 1 and

25 2 is greatly simplified in relation to a wiring diagram that describes in detail an embodiment of an apparatus in accordance with the invention. A more detailed sketch of a preferred embodiment of an apparatus in accordance with the invention included as a part of an apparatus for computer controlled micro-stepping of a two-phase stepping motor is illustrated in Figures 3a and 3b. The

30 apparatus illustrated in Figures 3a and 3b includes, inter alia, a two-phase stepping motor M, two integrated circuits PBL and PBM, delimited by dashed lines, a plurality of external components connected to connection points on the integrated circuits, and connections between the computer and one integrated circuit for control of the motor by the computer. Microprocessor control of

its respective current point memory LEVEL I1 and LEVEL I2. Each of the digital comparators is arranged to digitally compare the latest current value received directly from the data bus with the current values in the respective two memories, to decide whether the desired value time sequence has come  
5 into a period when its magnitude decreases and whether the latest current value is less than the value in LEVEL I1 or LEVEL I2. Each digital comparator, has circuits including a D-type flip-flop connected to its output for generation, on the respective output CD1 and CD2 of the integrated circuit, of a control limiting signal for the respective drive circuit of the first and second phase  
10 winding. The D-type flip-flops each has an enabling input E connected to the output E3 or the output E1 of the logic. Thus possible changes in the control limiting signals on the output CD1 and CD2 are synchronized in time with the enabling signals from E1 and E3 respectively. For example, the control limiting signal CD1 may have a low level when the absolute magnitude of the desired  
15 value for the first stator winding current is decreasing and is less than the current point value. In remaining cases, i.e. when the desired value is not decreasing or is greater than the current point value, the control limiting signal has a high level.

The integrated circuit in Figure 4 further has two digital to analogue converters  
20 DAC1 and DAC2, for converting the digital desired value from respectively DATA I1 and DATA I2 to an analogue value. The outputs of the converters are each coupled via their respective feedback amplifiers to respective outputs DA1 and DA2 on the integrated circuit, which integrated circuit furthermore has two outputs denoted SIGN1 and SIGN2. The signals on the outputs SIGN1  
25 and SIGN2 are obtained from the sign bits D7 for the respective digital desired value in respective DATA I1 and DATA I2, and denote the direction of the desired value current through the respective phase winding of the motor. A high level on SIGN1 and SIGN2 thus indicates a certain direction, and low level thereon denotes the opposite direction for the desired current through the  
30 respective phase winding. The outputs SIGN1 and SIGN2, as with the outputs CD1, DA1, CD2 and DA2 are connected to corresponding inputs SIGN1, SIGN2, I1<sub>R</sub>, CD1, I2<sub>R</sub> and CD2 in the integrated circuit in Figure 3b. This circuit is shown in more detail in Figure 5.

The integrated circuit in Figure 5 includes two principally alike drive circuits,

generate pulses on its output with a certain frequency independent of the desired values and actual values of the stator winding currents, these pulses being supplied to both the separate control means. The latter are also supplied a reference voltage obtained from the constant voltage on the input  $V_{CC}$  with the aid of a voltage divider R4 and R5.

The comparators OP10 and OP20 are adapted for comparing the respective desired current value with the actual value supplied to the inputs K1 and K2 from actual value transducers including respectively RG1, RF1, CF1 and RG2, RF2, CF2, the filters RF1/CF1 and RF2/CF2, respectively, having the task of attenuating transients coming from switching phenomena in the semiconductors of the drive circuits. The desired values as well as the actual values are supplied in the form of voltages to the respective input. The output signals from OP10 and OP20 are therefore principally logical signals, the levels of which say whether the respective actual value magnitude is greater or less than the respective desired value magnitude. In a corresponding way, OP11 and OP21 are adapted to compare the respective desired value magnitude with a small reference voltage across R5 and to generate logical output signals saying whether the respective desired value essentially exceeds zero or not. The outputs from respectively OP10, OP11 and OP20 and OP21 are connected to logic in respective separate control means adapted to generate individual control signals for the individual switches in the respective circuit connection in response to signals from the inputs CD1, SIGN1, OP10, OP11 and the pulses from OPA or in response to the signals from the inputs CD2, SIGN2, OP20, OP21 and the pulses from OPA. In response to the signals to the respective logic, the latter can control the switches in the respective drive circuit such as to enter into four different combinations of states, of which two enable energy supply from the current source to the respective phase winding with current in opposite directions through the respective phase winding. Of the remaining two, one combination enables feedback of energy from respective phase winding to its voltage source via respective drive circuit, while in the remaining combination there is neither any substantial energy supply from the voltage source to the respective phase winding nor any substantial feedback of energy from the respective phase winding to the voltage source. The combinations with associated operational states in the respective drive circuit are known per se to one skilled in the art in the illustrated drive circuit and are therefore not

direction through the respective phase winding have time to shut off before other switches have time to be put into a conductive state for driving current in the other direction through the respective phase winding. Since the logic comprises components known per se of the type AND-gates, inverting OR-gates and inverters provided with customary symbol denotations, further description  
5 of the logic ought to be completely unnecessary for one skilled in the art to understand the implementation of the invention.

The embodiment described so far in connection with Figures 3-5 provides a comparatively simple limitation of the possibility of controlling the respective  
10 drive circuit such as to enter into certain operational states. A somewhat more sophisticated limitation of the control possibilities may be obtained by modifying this embodiment in accordance with Figures 6 and 7. In Figure 6 there is illustrated a dividing means for dividing the period time  $T$  of the pulses from OPA into first and second time intervals  $T_1$  and  $T_2$ , and for actuating a  
15 control means so that entry into one operational state is inhibited during the first interval  $T_1$  and entry into another state is inhibited during the second time interval  $T_2$ . The dividing means includes a comparator, one input of which is intended for connection to the input RC on the integrated circuit in Figure 3b, and to have its other input connected to an adjustable reference voltage  $V_{REF}$ .  
20 The comparator is adapted to generate on one output a substantially logical signal with a level responding to whether the voltage on the input RC exceeds or falls below the reference voltage  $V_{REF}$ . If the latter has a value between the highest and lowest value of the voltage RC, which is almost sawtooth-shaped in time, there is obtained on the output of the comparator what is essentially a  
25 pulse train, the frequency of which concurs with the sawtooth voltage frequency and the pulse time relationship, i.e. the relationship between the time intervals  $T_1$  and  $T_2$ , depends on the magnitude of  $V_{REF}$ . The output of the comparator is connected to the respective input of two OR circuits intended for connection, one between the output CD1 and the input CD1 of the integrated  
30 circuits in Figure 3 and the other between the output CD2 and input CD2 of the integrated circuits in Figure 3.

With the aid of the dividing means the inputs CD1 and CD2 may be modified so that the respective control means is prevented during each period of the signal from OPA, firstly during a first time interval  $T_1$ , from putting the respective



To avoid any misunderstanding it is pointed out that in the embodiments described above, in all cases the limitations of the possibility of controlling into an operational state with comparatively rapid or comparatively slow current decline are limitations in time in response to the desired value time sequence.

5 In the described embodiments, the limitations are thus not dependent on how much the actual value differs from the desired value. For example, rapid current decline is not limited to the cases when the desired value is very much smaller than the actual value and slow current decline is not only applied in the cases where the desired value is only slightly less than the actual value. For

10 example, the absolute magnitude of the desired value and the magnitude of the actual value in relation to the magnitude of the desired value affect how large a part of the time interval T1 in Figure 7 during which the drive circuit is put into the first or second operational state. On the other hand, the magnitude of the actual value in relation to the desired value cannot affect the magnitude of

15 the time interval T1 in relation to the magnitude of the time interval T2 in the embodiment described in connection with Figures 6 and 7.

Also in order to avoid misunderstandings, it is pointed out that the respective desired value in the embodiments described above is not of the type to/from, but its magnitude can normally assume a large number of different values

20 between a greatest and a least. For example, 128 different values can be given digitally with 7 bits. For at least the majority of these the respective drive circuit is controlled alternately to enter into different operational states with an alternating frequency corresponding to the pulse frequency from OPA, and this pulse frequency should lie above the audible frequency range and could be

25 26.5 kHz, for example.

Figure 8 illustrates separately for each of four current control cases stepwise changing desired current values and corresponding actual current values obtained when the drive circuit is prevented from using the second and third operational states during certain times. In all cases illustrated in Figure 8 the

30 desired current value is given a zero reference level and magnification somewhat different than those of the corresponding actual current value to avoid interference. Thus the upper curve in each case illustrates the magnitude of the desired current values versus time whereas the lower curve in each case illustrates the magnitude of the actual current value versus time. In all four

is normally undesirable.

In the lower left case illustrated in Figure 8, the actual current curve was obtained when the drive circuit was prevented from using the third operational state during that part of the half sinus cycle which is to the left of the time  $t_x$ , and the drive circuit was allowed to use both the second and the third operational states during that part of the half sinus cycle which is to the right of the time  $t_x$ . During the time to the right of  $t_x$  the drive circuit was allowed to use the second operational state and the third operational state during separate alternating time intervals like T1 and T2 according to Figure 7. It appears from the curves of this case that the current ripple obtained in this case was substantially smaller than the current ripple obtained according to the previously described case. It also appears from the curves of this case that the drive circuit was able to decrease the actual current value as fast as the sinusoidal decrease of the desired current value at the end of the illustrated half sinus cycle.

In the lower right case illustrated in Figure 8 the stepwise changing of the desired current value with time is clearly visible. In this case it is also visible that the frequency of controlling the drive circuit into different operational states, i.e. the frequency of the pulsed from OPA in Figure 5, is much higher than the frequency of changes in the desired current value.

The invention is not limited to the described embodiments of the method and apparatus, and somewhat different embodiments are conceivable within the scope of the claims. For example, it is conceivable to use another drive circuit, known per se, which is controllable such as to provide the three different operational states. It is also conceivable to have a common current point memory for the currents of both phase windings instead of a separate one for the respective phase winding current.

a stepping motor in response to a desired value, which desired value successively increases during certain time periods and successively decreases during other time periods, which motor is supplied with energy from a voltage supply via a drive circuit, which drive circuit has at least three different operational states, in a first of the three operational states energy being supplied from the voltage source to the stator winding via the drive circuit, in a second of the three operational states no substantial energy being supplied to the stator winding from the voltage supply via the drive circuit and no substantial energy being fed back from the stator winding to the voltage supply via the drive circuit, in a third of the three operational states no substantial energy being supplied to the stator winding from the voltage source via the drive circuit but substantial energy may be fed back from the stator winding to the voltage supply via the drive circuit, in which method the current is sensed and an actual value corresponding to the sensed current is generated, the actual value is compared with the desired value, the desired value time sequence is sensed to determine whether the desired value is smaller or greater than at least one predetermined value independent of the actual value and to determine whether the desired value is increasing or decreasing, and the drive circuit is controlled to enter into one of the operational states in response to both the result of the comparison between the actual value and the desired value and the result of the sensing of the actual value time sequence.

4 A method as claimed in claim 1 or 3 wherein the drive circuit is controlled to enter into either the first or the second but not the third operational state when the desired value is increasing, and the drive circuit is controlled to enter into either the first or the third but not the second operational state during at least certain time intervals when the desired value is decreasing and less than a predetermined value.

5 A method as claimed in claims 2 or 4, characterized by generating a cyclic series of first time intervals (T1) and second time intervals (T2), and in that when sensing the desired value time sequence indicates that the magnitude of the desired value successively decreases, the possibility of controlling the switches so that their entering a) into the second combination of states is limited in time to the first time intervals (T1), b) into the third combination of states is limited in time to the second time intervals (T2).

desired value and a predetermined value independent of the actual value, and  
5 comparison means (DC1, DC2, DCOMP1, DCOMP2) for comparing a recent  
desired value with the desired value and the predetermined value stored in the  
memory means and generating a signal (CD1, CD2) in response to the result of  
the comparisons.

9 An apparatus as claimed in claim 8, characterized by time interval  
generating means (R1, R2, R3, OPA, SWA, SWB) for generating a cyclic  
sequence of first time intervals (T1) and second time intervals (T2), which time  
interval generating means are connected to prevent the use of the third  
5 combination of switch states during the first time intervals when the desired  
value decreases, and which time interval generating means are connected to  
prevent the use of the second combination of switch states during the second  
time intervals when the desired value decreases.

10 Apparatus as claimed in claim 9 for microstepping of a stepping motor,  
characterized by interval setting means ( $V_{REF}$ ) for setting the relative  
magnitude relationship between the first and the second time intervals  
independent of the magnitudes of the desired value and the actual value.

11 An apparatus for controlling current through a stator winding in a motor  
in response to a desired value, which desired value varies at least from time to  
time and has a magnitude which successively increases during certain time  
periods and successively decreases during other time periods, which motor is  
5 connected to a voltage source via a drive circuit, which drive circuit has at  
least three different operational states, in a first of the three operational  
states energy being supplied from the voltage source to the stator winding via  
the drive circuit, in a second of the three operational states no substantial  
energy being supplied to the stator winding from the voltage source via the  
10 drive circuit and no substantial energy being fed back from the stator winding  
to the voltage source via the drive circuit, in a third of the three operational  
states no substantial energy being supplied to the stator winding from the  
voltage source via the drive circuit but substantial energy may be fed back  
from the stator winding to the voltage source via the drive circuit, which  
15 apparatus comprises actual value means for generating an actual value  
corresponding to the actual current, comparison means for comparing the

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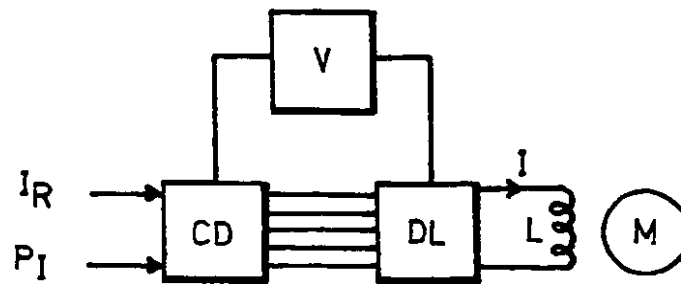


Fig.1

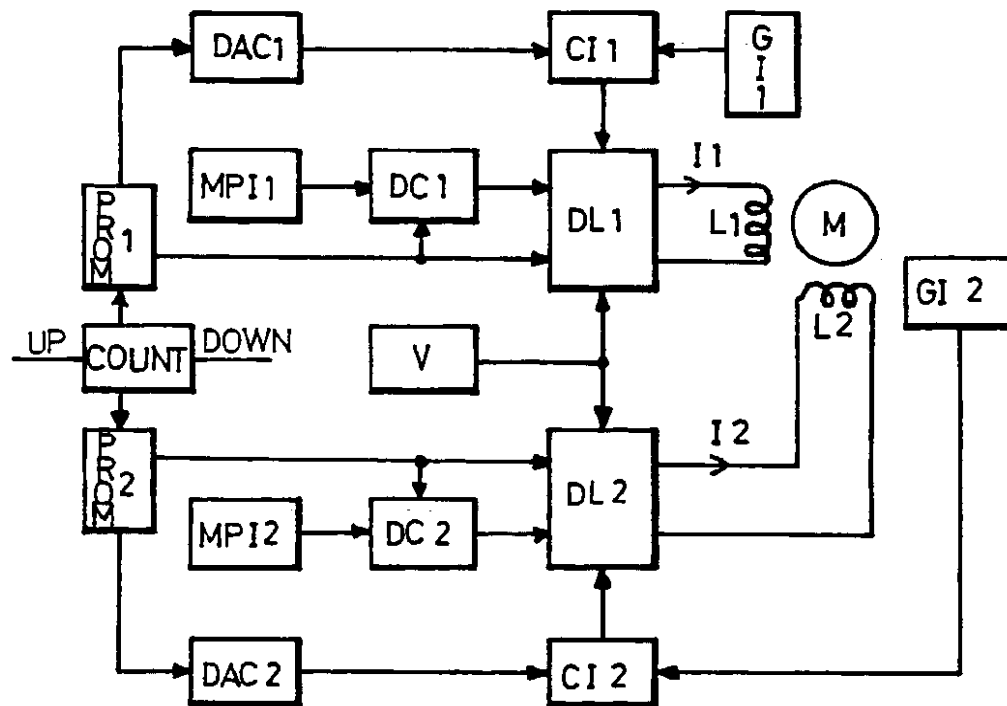


Fig.2

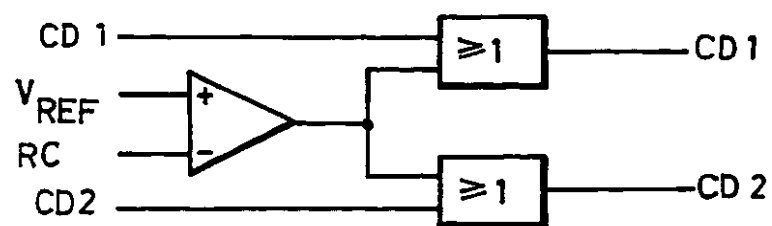


Fig.6

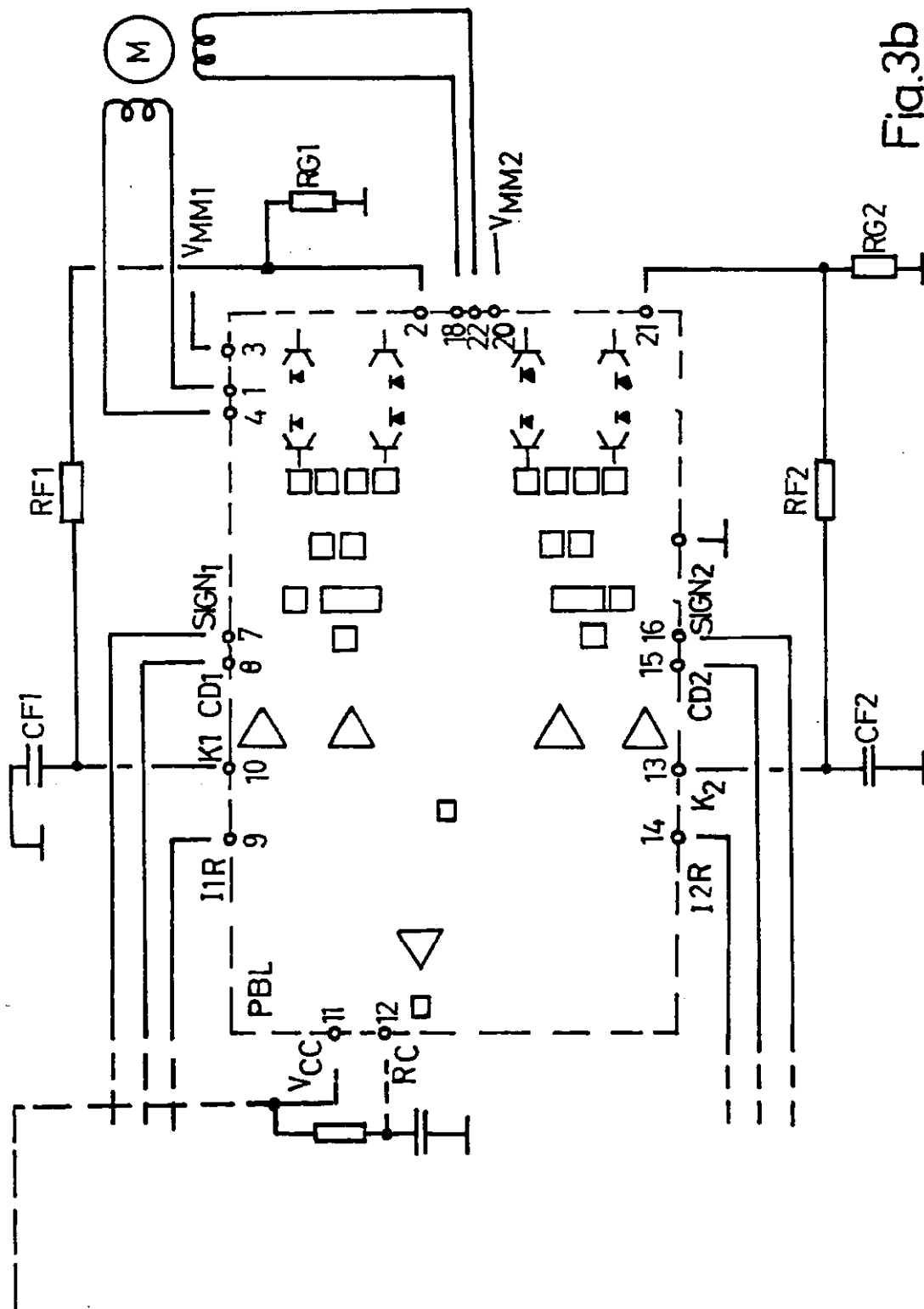


Fig. 3b

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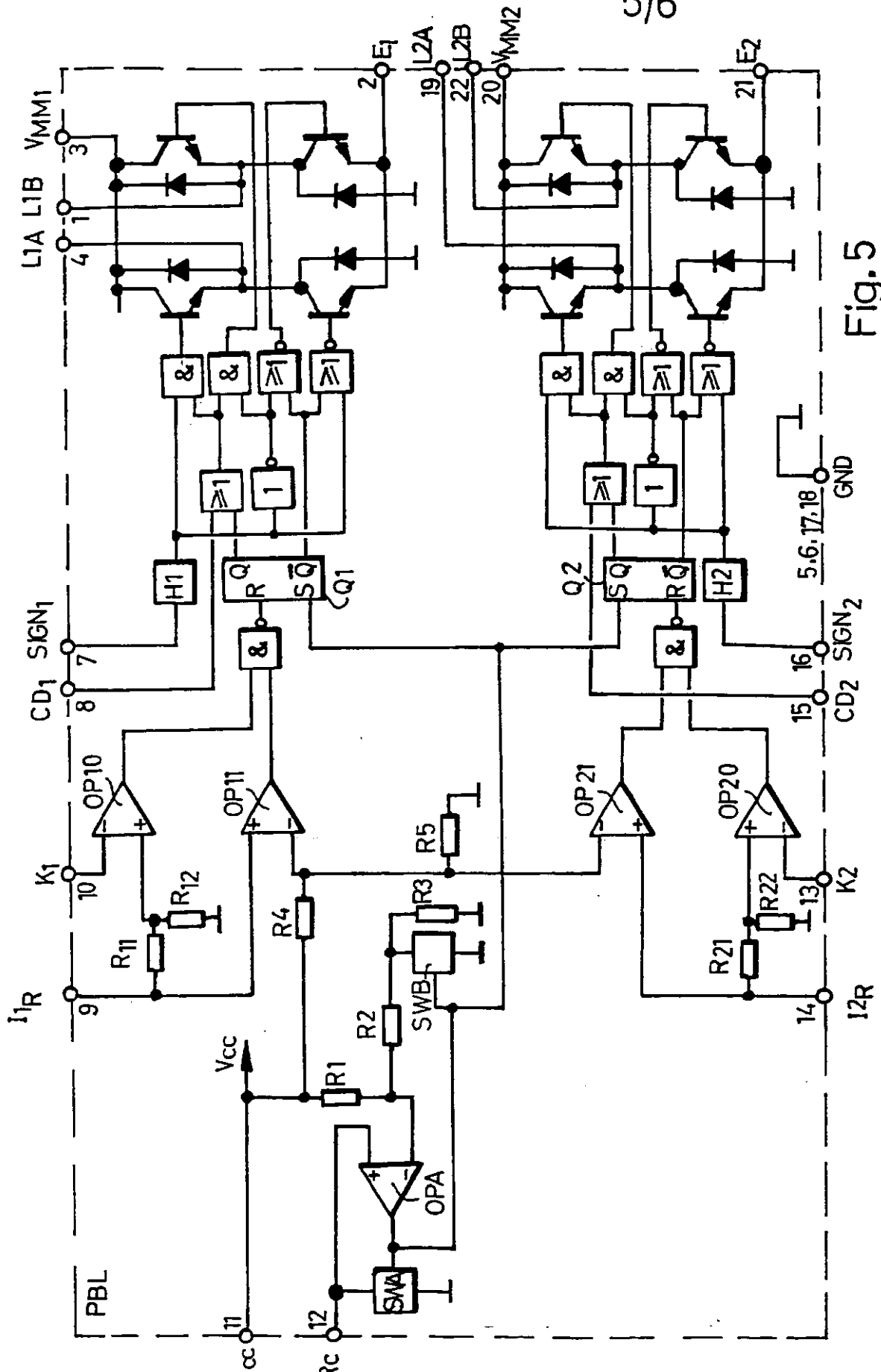


Fig. 5



European Patent  
Office

# EUROPEAN SEARCH REPORT

0242344  
Application number

EP 87850100.6

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
A	US-A-4 563 619 (CHLORIDE GROUP) * column 3, line 38 - column 4, line 40 *	1,7	H 02 P 6/02 H 02 P 8/00
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A	GB-A-2 022 345 (HAWKER SIDDELEY) * page 2, lines 54-79 *	1,7	
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			TECHNICAL FIELDS SEARCHED (Int. Cl.4)
			H 02 P
The present search report has been drawn up for all claims			
Place of search STOCKHOLM		Date of completion of the search 03-07-1987	Examiner SANDH H.
<b>CATEGORY OF CITED DOCUMENTS</b>			
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